Normal-state magnetotransport in $La_{1.905}Ba_{0.095}CuO_4$ single crystals

Yasushi Abe[1,2], Yoichi Ando[1,2], J. Takeya[1], H.Tanabe[3], T. Watauchi[3], I. Tanaka[3], and H. Kojima[3]
[1] *Central Research Institute of Electric Power Industry, Komae, Tokyo 201-8511, Japan*
[2] *Department of Physics, Science University of Tokyo, Shinjuku-ku, Tokyo 162-8601, Japan*
[3] *Institute of Inorganic Synthesis, Yamanashi University, Kofu, Yamanashi 400-8511, Japan*
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The normal-state magnetotransport properties of $La_{2-x}Ba_xCuO_4$ single crystals with x=0.095 are measured; at this composition, a structural transition to a low-temperature tetragonal (LTT) phase occurs *without* suppression of superconductivity. None of the measured properties (in-plane and out-of-plane resistivity, magnetoresistance, and Hall coefficient) shows any sudden change at the LTT phase transition, indicating that the occurrence of the LTT phase does not necessarily cause an immediate change in the electronic state such as the charge-stripe stabilization.

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$La_{2-x}Ba_xCuO_4$ (LBCO) has been generally considered as a rather peculiar high-T_c cuprate, not only because it is the first high-T_c cuprate discovered by Bednorz and Müller [1], but also because T_c of this compound is drastically suppressed in the composition rage near x=1/8 [2], known as the "1/8 anomaly". Soon after the 1/8 anomaly was recognized, it was found that LBCO system shows a structural phase transition from a low-temperature orthorhombic (LTO) phase to a low-temperature tetragonal (LTT) phase in a rather wide range of x around 1/8 [3,4]. On the other hand, $La_{2-x}Sr_xCuO_4$ (LSCO) system, which has the same crystal structure as LBCO, does not show a clear suppression of T_c near 1/8; since there is no structural transition to the LTT phase in LSCO [5,6], it is generally believed that the occurrence of the LTT phase is responsible for the suppression of T_c in LBCO.

There have been many experiments which tried to investigate the fundamental mechanism of the 1/8 anomaly. For example, Yoshida *et al.* studied the effect of partial substitution of Ba^{2+} ion in LBCO with smaller divalent cations and found that such replacement of Ba^{2+} leads to a suppression of the LTT structural transition and simultaneously to a recovery of the superconductivity [7]. This result suggests that the LTT transition temperature and the strength of the T_c suppression are closely tied to each other. Thus, Yoshida *et al.* concluded that the "1/8 anomaly" is caused by a Peierls-type mechanism with cooperative electronic and lattice instabilities. However, there are evidences which suggests that the occurrence of the LTT phase alone does not necessarily mean a destruction of superconductivity. Behaviors of $La_{2-x-y}Nd_ySr_xCuO_4$ (Nd-doped LSCO) system is one such example [8]. In this system, while there is a clear structural phase transition to the LTT phase at 71 K and the superconductivity is almost completely destroyed for x=0.12, there remains a bulk superconductivity (with T_c=16 K) for x=0.20 even though the LTT phase transition temperature T_{LTT} is higher (79 K) than that for x=0.12. Since high-quality single crystals are available for Nd-doped LSCO, the in-plane resistivity ρ_{ab} and the out-of-plane resistivity ρ_c have been studied in this system [8]. For x=0.12, both ρ_{ab} and ρ_c show a clear jump at T_{LTT}, suggesting that the electronic state is changed upon the structural phase transition. It was found that ρ_c shows a jump at T_{LTT} even for x=0.20, indicating that the change in the electronic state persists to the x value where the suppression of superconductivity is weak.

The known properties of LBCO is quite similar to that of Nd-doped LSCO; superconductivity is almost completely destroyed at x=1/8, bulk superconductivity remains for $x\neq$1/8, and the structural phase transition to the LTT phase occurs around 60 K which is almost independent of x. However, because of the difficulty in growing single crystals of LBCO, the anisotropic resistivity and the magnetotransport properties have not been well studied in LBCO with x near 1/8 and thus the electronic states near x=1/8 is not well understood.

One of the composition of particular interest in LBCO is x=0.09; around this composition, the structural phase transition takes place but T_c is not suppressed ($T_c\simeq$30 K). In other words, the superconductivity for x=0.09 does not seem to be affected by the occurrence of the LTT phase. It is thus interesting to study whether the electronic system shows any change at the LTT phase transition for x=0.09, where the LTT phase does not affect superconductivity at all. This may clarify the importance (or unimportance) of the occurrence of the LTT phase to the electronic structure.

With the improvement in the crystal growth technique, high-quality single crystals of LBCO with x near 1/8 have recently become available [9,10]. In this paper, we report our detailed measurement of the anisotropic normal-state resistivity (ρ_{ab} and ρ_c), in-plane magnetoresistance (MR), and the Hall coefficient R_H, of LBCO single crystals with x=0.095. As discussed above, this is the particular composition where T_c is not suppressed despite the presence of the LTT phase. In fact, our x=0.095 crystals showed mid-point T_c of 31 K, a very high value for LBCO. It was found that none of the measured transport properties shows any drastic change at the LTT phase

transition, which strongly support the picture that the occurrence of the LTT phase does not necessarily change the electronic system.

The question whether the occurrence of the LTT phase alone can be responsible for the change in the electronic state is particularly intriguing in the light of the recently reported "stripe order" in the Nd-doped LSCO with x=0.12; using neutron diffraction techniques, Tranquada *et al.* observed elastic magnetic superlattice peaks of the type (1/2$\pm\epsilon$,1/2,0) and charge-order peaks at (2$\pm$2ϵ,0,0), where ϵ=0.118 at low temperatures [11,12]. Such an observation strongly suggests a presence of a one-dimensional charge order ("stripes") which intervene in the antiferromagnetic spin order. Tranquada *et al.* proposed that the modulated antiferromagnetic order is pinned and stabilized in the LTT phase but not in the LTO phase, which is the reason why such static structure is not observed in pure LSCO. Following this picture, it can be inferred that the fundamental origin of the change in the electronic state in Nd-doped LSCO is the occurrence of the stripe phase and not the occurrence of the LTT phase itself. If so, it may be that the stripe order is *not* stabilized by the LTT phase transition in LBCO at x=0.095, which can be the reason for the coexistence of a "high" T_c of 31 K with the LTT phase.

The single crystals of $La_{1.905}Ba_{0.095}CuO_4$ are grown using a traveling-solvent floating-zone (TSFZ) technique. Details of the crystals growth of LBCO are described elsewhere [9]. After the crystallographic axis are determined, we cut the crystals to sufficiently small dimensions, typically 2 $\times$ 0.4 $\times$ 0.1 mm^3, to ensure homogeneous Ba concentration in the crystal. The crystals are annealed in flowing-oxygen atmosphere at 650°C for 24 hours to remove oxygen deficiencies. The actual Ba concentrations in the crystals are determined by the inductively-coupled plasma spectrometry (ICP) technique. A standard six-terminal method is used for the simultaneous ρ_{ab} and R_H measurement. Both the MR and R_H data are taken in the sweeping magnetic field at fixed temperatures with an ac technique. The temperature is very carefully controlled and stabilized using both a capacitance sensor and a Cernox resistance sensor to avoid systematic temperature deviations with magnetic fields. The stability of the temperature during the MR and R_H measurements is within 10 mK.

Figure 1 shows the temperature dependence of ρ_{ab} and ρ_c. These data are measured in two different samples cut from the same rod. In both samples, the onset T_c is 33 K and the resistivity becomes zero at 29 K. ρ_{ab} is linear in T down to 150 K and shows an upward deviation from the T-linear behavior at lower temperatures. A slight upturn in ρ_{ab} is observed below 45 K, which is consistent with the data on polycrystalline samples around this composition [13]. The extrapolated residual resistivity is negligibly small, which is similar to the behavior of high-quality LSCO crystals [14]. In the case of Nd-doped LSCO, clear jumps in both ρ_{ab} and ρ_c have been observed at T_{LTT} in underdoped samples [8]; however, there is no clear jump neither in ρ_{ab} nor in ρ_c in LBCO as shown in Fig. 1. Note that the structural phase transition to the LTT phase takes place at about 60 K for this x value in LBCO [15]. Therefore, contrary to the Nd-doped LSCO system, the resistivity data suggest that there is no sudden change in the electronic system in LBCO with x=0.095 at T_{LTT}. If we look at the temperature dependence of $d\rho_{ab}/dT$ (Fig. 1 inset, upper curve), there is a kink near T_{LTT} ($\simeq$60 K), which may suggest that the scattering of electrons gradually increases in the LTT phase. On the other hand, $d\rho_c/dT$ (Fig. 1 inset, lower curve) does not show any change at T_{LTT}, although there is a kink at lower temprature, about 52 K. It is intriguing that $d\rho_{ab}/dT$ and $d\rho_c/dT$ show kinks at different temperatures.

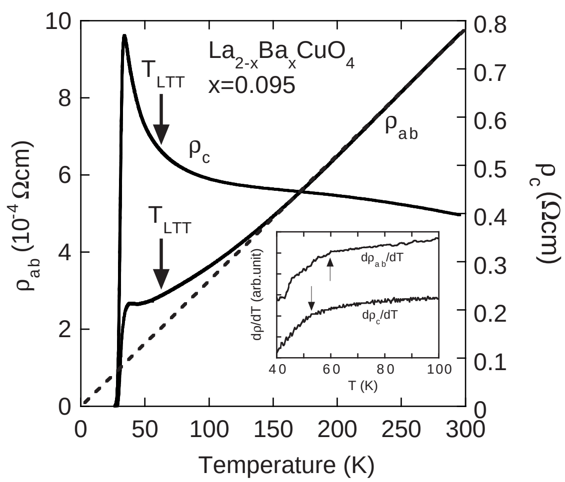

FIG. 1. T dependence of ρ_{ab} (left-hand-side axis) and ρ_c (right-hand-side axis). T_{LTT} is indicated by arrows. Inset: Plot of $d\rho_{ab}/dT$ and $d\rho_c/dT$ vs T. Arrows mark the kinks.

Figure 2 shows the temperature dependence of the in-plane R_H. Here, the magnetic field is applied along the c axis and the current is along the ab plane. For comparison, $R_{\rm H}$ data of LSCO (x=0.1) polycrystalline sample [16] are also shown by a dashed line. R_H of LBCO shows a peak at about 50 K, which is nearly the same temperature where ρ_{ab} starts to show an upturn. There is no appreciable change in R_H at T_{LTT} (=60 K). The behavior and the absolute value of the R_H of our LBCO crystal are quite similar to that of LSCO (x=0.1) system, which does not show an LTT phase transition.

One popular way of analyzing the normal-state transport properties of cuprates is to consider two scattering times, τ_{tr} and τ_H [17]. $\tau_{tr}(T)$ and $\tau_H(T)$ are determined by the temperature dependence of $\rho_{\rm ab}$ and the cotangent of the Hall angle $\theta_{\rm H}$, respectively [18]. Figure 3 shows $\cot\theta_{\rm H}$ ($=\rho_{xx}/\rho_{xy}$) at 10 T plotted against T^2. Since the Hall angle is proportional to the inverse of $\tau_{\rm H}$, it is clear from Fig. 3 that $\tau_{\rm H}^{-1}$ obeys a T^2 law very well across T_{LTT} down to 45 K. (The inset to Fig. 3 is a modified

plot of the main panel to show directly the temperature region where the T^2 law holds.)

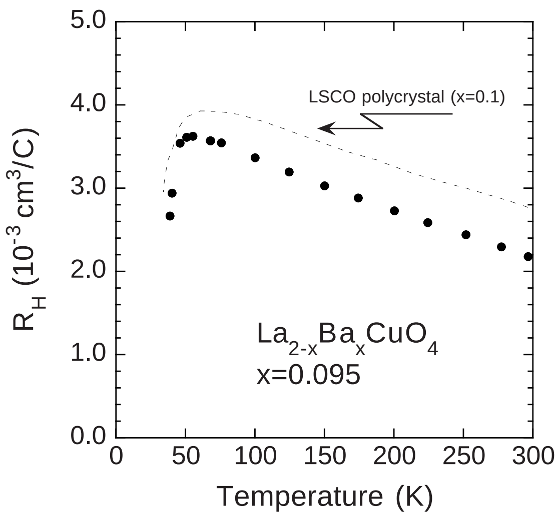

FIG. 2. T dependence of the Hall coefficient R_{H}(T) (solid circles). The dashed line is the $R_H(T)$ data of LSCO (x=0.1) polycrystalline sample from Hwang *et al.* [16].

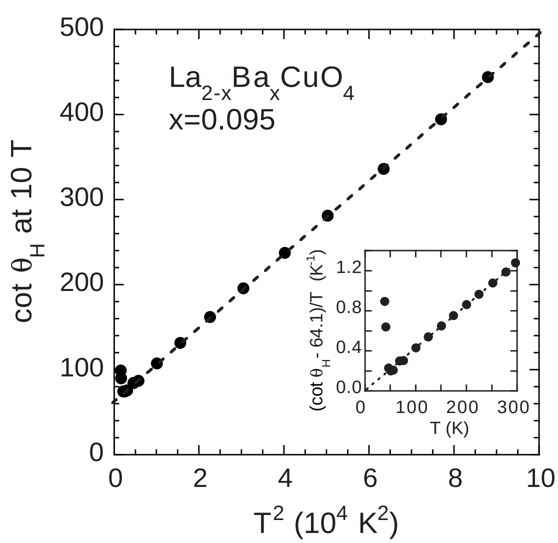

FIG. 3. T^2 plot of $\cot\theta_H$ at 10 T. The dashed line is a fit to the data with $\cot\theta_{\mathrm{H}} = a + bT^2$ (a=32.1 and b=21.3). Inset: A modified plot of the main panel to show that the T^2 law holds down to 45 K.

Figure 4 shows the result of the MR measurements of the LBCO crystal. We measured both the transverse MR (I is within the ab plane and H is parallel to the c axis) and the longitudinal MR (I and H are within the ab plane and H is parallel to I). The transverse MR consists of orbital and spin contributions, while the longitudinal MR comes only from the spin contribution. By comparing the two MRs, we can see that the spin contribution to the transverse MR is not large (about 30%). Although the longitudinal MR shows a smooth increase down to 40 K, the transverse MR shows a rather steep increase below 60 K, resulting in more than an order-of-magnitude difference between the two MRs at 40 K.

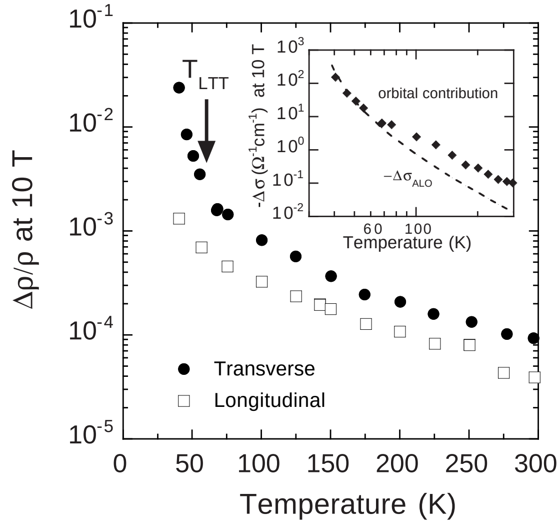

FIG. 4. T dependence of the transverse MR (sold circles) and the longitudinal MR (open squares) at 1 T. The arrow shows T_{LTT}. Inset: Orbital part of MR and the estimated AL orbital fluctuation conductivity (dashed line).

We tried to analyze whether this steep enhancement in the transverse MR can be understood by the superconducting fluctuation conductivity, whose contribution is large only for the transverse geometry. The fluctuation conductivity consists of Aslamasov-Larkin (AL) term and Maki-Thompson (MT) term; both terms comprises two contributions, the orbital contribution and the spin contribution [17]. Kimura *et al.* have analyzed the MR in underdoped LSCO and concluded that the MT term is absent [14], which is actually expected for a d-wave superconductor [19]. Thus we tried to estimate the fluctuation conductivity by considering only the AL term. The dashed line in the inset to Fig. 4 is the estimated AL orbital contribution, where the parameters are $\xi_{\mathrm{ab}}(0)$=30 Å and $\xi_{\mathrm{c}}(0)$=1 Å. (We just assumed these values as typical values.) The orbital part of MR, which is obtained by subtracting the longitudinal MR from the transverse MR, is also plotted in Fig. 4. Clearly, the increase of the transverse MR below 60 K can be accounted for by the superconducting fluctuations; therefore, it is not likely that the steep increase in the transverse MR is related to the occurrence of the LTT phase.

It has been proposed that the orbital MR in high-T_c cuprates reflects the variance of a local Hall angle around the Fermi surface and therefore is proportional to the square of θ_{H} [20], which is sometimes called "modified Kohler's rule". Figure 5 shows the temperature dependence of the orbital MR plotted together with $a \times (\cot\theta_{\mathrm{H}})^{-2}$, where a is a fitting parameter. [Note that

$(\cot\theta_{\rm H})^{-2} \simeq \theta_{\rm H}^2$ when $\theta_{\rm H}$ is small.] The orbital MR does not scale so well to $(\cot\theta_{\rm H})^{-2}$. Particularly, the orbital MR shows weaker temperature dependence above $\sim$200 K compared to $(\cot\theta_{\rm H})^{-2}$. This might be an indication that the modified Kohler's rule is not universally applicable to all high-T_c cuprate. It would be interesting to study the applicability of the modified Kohler's rule to the LBCO system in a wider carrier-concentration range.

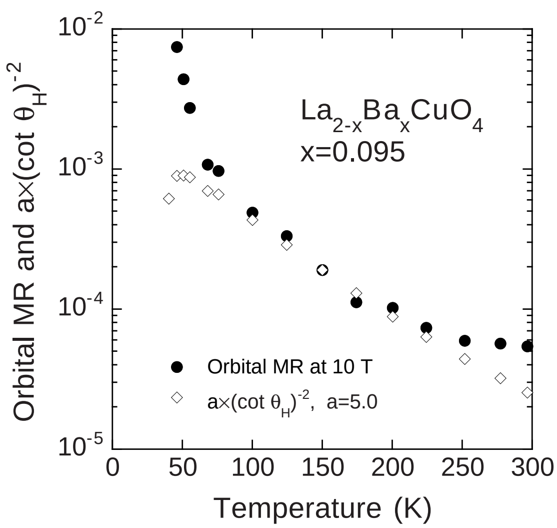

FIG. 5. Orbital MR and $a \times (\cot\theta_H)^{-2}$ vs T.

The above results indicate altogether that the electronic system as inferred from $\tau_{\rm H}$ and τ_{tr} does not show any sudden change at the LTT phase transition, which seems to be different from the result of Nd-doped LSCO [8]. In particular, the fact that $\cot\theta_{\rm H}$ shows a good T^2 behavior down to 45 K (Fig. 3) suggests that $\tau_{\rm H}$ is not influenced by the LTT phase. On the other hand, τ_{tr}^{-1} seems to grow gradually with lowering temperature in the LTT phase, which causes a faster increase in resistivity. Based on these observations, we may conclude that the coexistence of a "high" T_c of 31 K with the LTT phase is possible in LBCO at x=0.095 because the LTT phase transition does not immediately affect the electronic system. This, however, does not rule out the possibility that the electronic system is gradually changed in the LTT phase. The localization behavior in ρ_{ab} below 45 K might actually be the result of some gradual change in the electronic state.

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